Benchtop Porosity Measurement Technique Using Electrical Capacitance Tomography (ECT) Sensor

by

Mohamad Farid bin Ali
13522

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Petroleum)

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Universiti Teknologi PETRONAS
Bandar Sri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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(AP. Ir. Dr. Idris bin Ismail)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(MOHAMAD FARID BIN ALI)

ABSTRACT

This report consists of five chapters which are introduction, literature review, methodology, expected results and conclusion. The introduction of the report mentioned the background study of the project, followed by problem statement, objectives and the scope of study. The main objective of this project is to design a sensor called Electrical Capacitance Tomography (ECT) to measure porosity in a core sample. The conventional techniques used in lab, using Helium Porosimeter and Water Saturation methods are performed for comparison purposes. The literature review explained about the research done on topics, related to the project such as the design of ECT sensor and porosity measurement. ECT sensor is used to visualize and measure the permittivity distribution of a cross sectional area of vessel. The measurement is done by using multi-electrode capacitance sensor. For the methodology, it consisted of research methodology process flow, the project activities with the aid of key milestones diagram, the tools needed for the success of the project and experimental procedure to run the experiment. The project started by designing and fabricating the ECT Sensor. The ECT Sensor would then be used to measure porosity of core sample. The result will be in terms of tomography image, and porosity of the rock sample would then be measured. The porosity measured from ECT sensor would be compared with the conventional technique of porosity measurement in lab to identify the effectiveness of ECT sensor in measuring porosity. Based on the result, the measurement of ECT shows error more than 10% of the porosity value measured using helium porosimeter and water saturation technique. The ECT sensor may not be effective to measure porosity, yet with further improvement, the possibility of measuring and visualizing the porosity distribution of core sample can be done.

ACKNOWLEDGEMENT

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LIST OF ABBREVIATIONS

Electrical Capacitance Tomography	ECT
Polyvinyl Chloride	PVC
AC – Based Electrical Capacitance Tomography	ACECT
Petrographic Image Analysis	PIA

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The background of this project covers the study of Electrical Capacitance Tomography (ECT) and porosity measurement, by utilizing ECT Sensor. The project's basic idea is to design a portable benchtop sensor that utilizes ECT technique with the image reconstruction of porosity distribution in core sample. As every material has its own dielectric properties, therefore when the two different materials are being measured using ECT, the ECT can detect the dielectric properties of both material. It will send the data to the data acquisition system and it will convert the result into image of tomogram. For this project, sandstone core sample is used as the measurement medium as it gives the most accurate insight into the porosity of the reservoir rocks in the well.

1.1.1 ECT Sensor

Developed since 1980s, ECT is established for industrial process imaging that consists of dielectric materials. The technology of ECT is based on the measurement of the changes in capacitance as a result of change in dielectric distribution.[1] Multi-electrode sensor is placed surrounding the vessel of pipeline in order to give the measurement of the capacitance. As the reading of capacitance is obtained, the cross-sectional distribution of permittivity is reconstructed using mathematical algorithm. The good thing about the ECT technology is that the response is rapid, low cost to construct, non-intrusive and non-invasive and also able to withstand high pressure and high temperature[1].

1.1.2 Porosity

Porosity is the measure of storage capacity of reservoir. It is defined as the ratio of the pore volume to bulk volume. The pore volume is the volume of pore space inside the rock, while the bulk volume is equal to the overall volume of the rock. Porosity is one of the most important elements for petroleum engineers. As the value of porosity of rock has been determined, engineers can finally decide whether the rock formation is worth to be explored or not.

1.2 Problem Statement

Porosity is one of the main characteristic of reservoir rocks, where the other one will be permeability. Porosity indicates the amount of hydrocarbons trapped in the formation of the reservoir. A more porous reservoir rock contains more porous space inside it. There are several ways to measure and image porosity distribution inside the rock, like X-ray CT scanning to provide image distribution, and laboratory tools to measure porosity like helium porosimeter technique.

The X-ray CT scanning, although it can provide good quality image of porosity distribution inside the rock, is expensive. Therefore a cheaper alternative can be introduce in terms of Electrical Capacitance Tomography (ECT) which also provide image distribution on the tomogram, with less quality image.

Helium Porosimeter is one of the standard equipment in the lab to measure porosity. The equipment needs constant supply of Helium gas, thus it is not suitable to be relocated outside of the lab. The alternative, ECT is a portable device which can be used outside of lab, and possibly on the field as well; make it a portable and easy to use device in the field.

1.3 Objectives

The main objective of this project is to test the suitability of using ECT sensor as a tool to measure porosity in core sample. The details of the objectives were as follows:

1. To design and fabricate a workable ECT sensor.

This part includes the designing of the ECT sensor concept as well as fabrication part. The design of the sensor involves lots of consideration in order for it to be usable.

2. To measure the porosity of core sample

For this part, the sensor will be used to measure the porosity distribution of the core sample. The result from the ECT measurement will be compared against the helium porosimeter method and water saturation method to determine the effectiveness of ECT in measuring porosity.

1.4 Scope of Study

The scope of the study for this project will be divided into four main categories. The first part will be about the overview of porosity in rock. The second part will be the study of the overview of Electrical Capacitance Tomography (ECT). Under this scope, a little bit about the history of ECT is explained as well as on how the ECT works. The third part will cover about the design of ECT. The design of ECT is crucial as it will be implemented in fabricating the sensor. The design must be right in order to effectively measure the porosity. The final part of the study is the porosity measurement. Under this scope, the porosity will be measured using the ECT in terms of image pixel calculation. The result will then be compared with the result from the conventional technique of measuring porosity using Helium Porosimeter and Water Saturation.

1.4.1 Relevancy of the Project

Porosity Measurement using Electrical Capacitance Tomography (ECT) is relevant to the study of Petroleum Engineering as it explore the possibility of measuring porosity using a new alternative. Although the design of the sensor involves electrical concept, however, the sensor ECT is widely in the industry like measurement of flow of fluids in pipes as well as measurement of concentration of one fluid in another. Therefore, it is possible to implement the application of sensor ECT in petroleum engineering study scope to measure porosity.

1.4.2 Feasibility of the Project within the Time Scope and Frame

The time scope and time frame is referred as the project key milestone and gantt chart. 23 weeks are allocated for the student to accomplish their final year project, comprising of two semesters. The preparation of the project started with the collection of related materials for reading and understanding like books, journals and technical papers on ECT application and porosity measurement. Throughout the schedule, research will be conducted from time to time in order to have a better insight of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Porosity

Porosity is explained as the measure of space available for the accumulation and storage of fluid in the rock[2]. It denotes the fraction of rock pore space which is void. Based on figure 1, there are spaces available in between the mineral grains, called porosity.

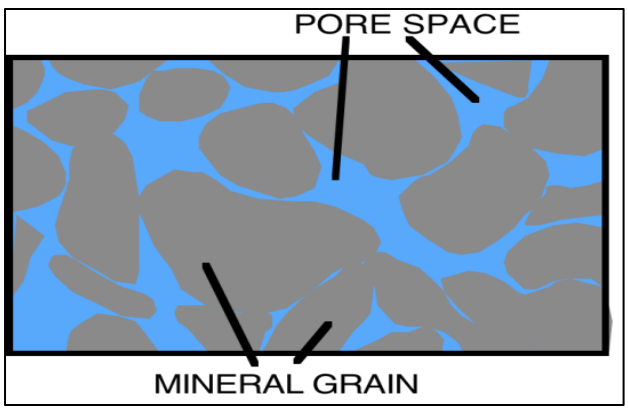


FIGURE 1. Pore Space Visualization[3]

Porosity was developed due to excessive cementation of the sediments, as the sediments were deposited and rocks begin to form during previous geological time, as some void spaces were created and became isolated from other void spaces. While some of the void spaces are connected to each other, some are completely isolated. This has led to two different types of porosity, which are[4]:

1. Absolute porosity
2. Effective porosity

2.1.1 Absolute Porosity

Absolute porosity is explained as ratio of total pore space in rock to the bulk volume[4]. Although the rock may have vast amount of absolute porosity, yet the absence of interconnectivity among the pore spaces will hinder the flow of hydrocarbon inside the rock.

2.1.2 Effective Porosity

For effective porosity, it is defined as the percentage of interconnected pore space against the bulk volume. For reservoir engineering calculation, effective porosity is the value used for the calculation instead of absolute porosity as effective porosity represents the interconnected pore space that contain recoverable hydrocarbon fluids.

There are several factors that affect porosity measurement[5]:

1. Grain Size/Shape

As the particles inside the pore space become more angular, the porosity will be increased as well.

2. Grain Packing

Different packing arrangement gives different porosity. The porosity decreases as compaction in packing increases.

2.2 Porosity Measurement

To measure porosity, it can be done through volumetric measurement of core samples or from geophysical logs where the logs measure property of the rock and the porosity, or from Petrographic Image Analysis (PIA), a pore level evaluation of a small sample size. Although the measurement of porosity from logging device yields higher value as compared to measurement using core sample, the core sample analysis has an advantage where no assumption shall be made to the likes of mineral composition and borehole effect[6]. Therefore, for this project, it is only focused on the porosity measurement from core samples of rock for simplification.

There are three parameters which are important is measuring porosity. They are:

1. Pore Volume – Represent the volume of void space inside rock.
2. Grain Volume – Represent the volume of grain inside rock.
3. Bulk Volume – Represent the overall physical volume of rock.

The relationship between the pore volume, the grain volume and the bulk volume will be represented in these equations[4]:

$$\emptyset=\left(\frac{\text{Pore Volume}}{\text{Bulk Volume}}\right)\times 100 \qquad \text{Eq. (1)}$$

$$\emptyset=\left(\frac{\text{Pore Volume}}{\text{Grain Volume}+\text{Pore Volume}}\right)\times 100 \qquad \text{Eq. (2)}$$

$$\emptyset=\left(\frac{\text{Bulk Volume-Grain Volume}}{\text{Bulk Volume}}\right)\times 100 \qquad \text{Eq. (3)}$$

The value of porosity is important in determining whether the rock formation is worth exploring. Table 1 will describe the percentage of porosity values[7].

TABLE 1. Description of Porosity Values

Description	Porosity Values (%)
Negligible	0 - 5
Poor	5 - 10
Fair	10 - 15
Good	15 - 20
Very Good	20 - 25
Excellent	>25

2.2.1 Porosity Measurement Technique using Helium Porosimeter

In the industry, there are several techniques which can be used to measure the porosity of the core sample of a rock in the lab. For this project, the ECT sensor will go head to head with the helium porosimeter porosity measurement.

Helium gas is used because helium molecule is light; therefore it allows the helium molecule to flow into the small pore of core sample easily. The helium porosimeter used Boyle-Mairotte's Law in order to determine the grain volume, bulk volume, pore volume, grain density and effective core porosity percentage. The Boyle-Mariotte's Law can be expressed as in equation 4, equation 5 and equation 6 as follows[6]:

Pore Volume: $$\text{Pore volume}= \frac{P_{\cdot ref}}{P_{\cdot exp}} \times V_{\cdot ref} - V_{\cdot dead} \qquad \text{Eq. (4)}$$

Grain Volume: $$\text{Grain Volume}=(V.\text{matrix} + V.\text{ref}) - \frac{P_{\cdot ref}}{P_{\cdot exp}} \times V_{\cdot ref} \qquad \text{Eq. (5)}$$

Bulk Volume: $$\text{Bulk Volume}=\left(\frac{\pi D^2}{4}\right) \times L \qquad \text{Eq. (6)}$$

$P_{ref.}$ = Reference Pressure (Initial Pressure)

$P_{exp.}$ = Expanded Pressure (Final Pressure)

$V_{ref.}$ = Reference Volume (Initial Volume)

$V_{exp.}$ = Expanded Volume (Final Volume)

V_{dead} = Gas Volume gathers surrounding the core

V_{matrix} = Volume of matrix cup

2.2.2 Porosity Measurement Using Saturation Method

For this method, bulk volume and pore volume is measured to get the porosity of the core sample. Although bulk volume can be calculated from measurement of the uniform core sample dimension, the usual procedure is to observe the volume of fluid displaced by the core sample. It can be seen either volumetrically or gravimetrically. Either way, it is necessary to prevent the fluid from penetrating the pore space of the core. In order to achieve that, the core sample shall be coated with paraffin. The gravimetric determinations of bulk volume will then be observed by measuring the weight loss of the sample when immersed in a fluid.

For pore volume, the pore volume can be determined by extracting initial fluid inside the core sample using vacuum. Distilled water is used to fill up the void pore space of the sample. From there, the difference between the dry weight of the rock sample and the weight of the core sample in wet condition will produce the pore volume as stated in equation 7.

The effective porosity can be measured once the pore volume and bulk volume have been determined.

$$V_P = \left(\frac{W_W - W_d}{\rho_{water}}\right) \qquad \text{Eq. (7)}$$

V_p = Pore volume

W_w = Weight of saturated core sample

W_d = Weight of dry core sample

P_{water} = Water density

2.3 Core Sample

The core sample used for the measurement of porosity using ECT sensor will be sandstone as it is widely available and it is much easier to measure porosity compared to carbonate core sample. The porosity of core sample is varied by depth and location of the wells[9]. In addition with depth and location, the core sample is also affected by overburden pressure[10]. Therefore it is important to use the same core sample for all experiments in the Helium Porosimeter, Water Saturation and ECT Sensor. This is to ensure that the data acquired from all experiments are valid to be compared against each other. Core samples come in various sizes. The most common core sample used is having 1.5 inch in diameter while the length is at 3 inch. Figure 2 shows the example of core sample used in porosity measurement.

FIGURE 2. Sandstone Core Sample[8]

2.4 Electrical Capacitance Tomography

Electrical Capacitance Tomography is technique that assessing variations in the dielectric properties of material in the region it measure, like in closed pipes or vessels. Among the information obtained from Electrical Capacitance Tomography are cross-sectional images of the vessel contents and the volume fraction of the contents of the vessels. In the basic Electrical Capacitance Tomography system, it consists of three main parts, which are:

1. The Electrical Capacitance Tomography (ECT) sensor
2. The data acquisition unit/capacitance measuring unit
3. Control computer
4.

2.4.1 Measurement Principle

This is how the ECT works. A set of electrodes are attached around a pipe vessel. Electrodes are surrounding the cross section of the contents that ECT is going to image. From there, the ECT measures the electrical capacitance between the electrodes pairs. The information is then used to create an image of the contents, as it measures the capacitance between the electrode pairs. As the ECT captures the data, it will translate the measurement data into image permittivity distribution through the data acquisition system.

As the sensing electrodes are not in physical contact with the contents inside, the ECT sensor is claimed to be noninvasive and nonintrusive[11]. Even if the electrodes are in contact with the contents inside the pipe, as long as they do not obstruct the flow in any way, the ECT sensor is still considered as noninvasive.

2.5 Sensor Design

In designing ECT, there are several parameters that need to be considered. Figure 3 shows the complete configuration model of ECT, from the sensor, to the data acquisition system and the control computer. The lists of parameters will be as followed:

1. Capacitance measurement concept
2. Electrodes number
3. Electrodes length
4. External and internal electrodes
5. Earthed screen
6. Normalization of Measurement

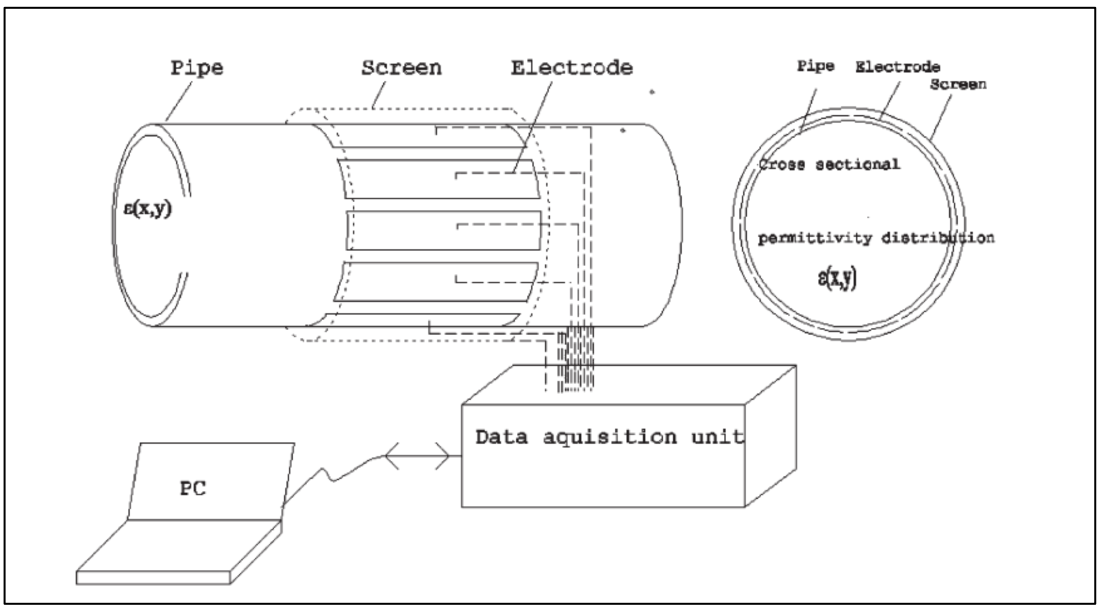


FIGURE 3. Electrical Capacitance Tomography Model[12]

2.5.1 Capacitance Measurement Concept

A capacitor is a device that stocks electric charges. It comes with various size and shape, however the simple configuration is when two conductors carrying equal but opposite charges. In the uncharged state, the charge on either one of the conductors in the capacitor is zero. During the charging process, a charge Q is moved from one conductor to another, giving one conductor a charge +Q, while the other one is charge –Q. The result of the charging process created potential difference, V. The relationship between the magnitudes of charge against voltage can be seen in the equation 8:

$$C=\frac{Q}{V} \qquad \text{Eq. (8)}$$

C = Capacitance

Q = Charge

V = Voltage

2.5.2 Electrodes Number

Deciding the number of electrodes will be the first step in designing ECT sensor. Several advantages are expected by considering small number of electrodes to be used in designing ECT sensor[12].

By adopting smaller number of electrodes, a smaller number of data acquisition channels can be used.

1. Faster data acquisition rate
2. Reducing the length of electrodes as the increased of cover angle of the electrodes gives an increased in inter-electrode capacitance.

Somehow, by adopting a small number of electrodes, a good image shall not be expected, as the independent capacitance measurement is small. Although by using large amount of electrodes will result in good image, it will also bring several problems to the ECT. They are:

1. The ECT will be hard to design and fabricated, making it an expensive tool.
2. The capacitance to be measured is smaller.

3. Additional measurement are recorded, thus will effect in slower rate of data acquisition.

The number of independent capacitance measurement can be expressed as in equation 9:

$$\text{Independent capacitance measurement} = \frac{N(N-1)}{2} \qquad \text{Eq. (9)}$$

N = Number of electrodes used

Therefore, if the number of electrodes which is going to be used in the ECT is 12, the number of independent capacitance measurement will be 66. Figure 4 shows the on how the electrodes are mounted on the insulating pipe or the sensor body while Table 2 shows the relationship between the number of electrodes and the number of independent measurement they produce together with the application. By having more number of electrodes, the typical speed frames are reduced due to increasing number of independent measurement.

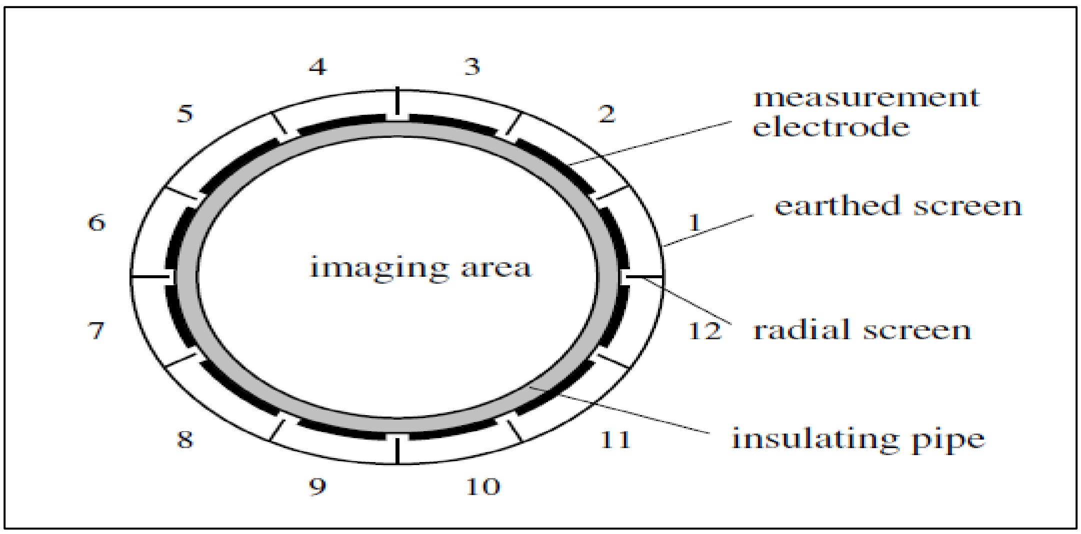


FIGURE 4. Number of Electrodes[12]

TABLE 2. The Relationship of Electrodes Number and Independent Measurements

No. of Electrodes	No. of Independent Measurement	Typical Speed (frames/s)	Example of Application	References
6	15	400	Combustion flame in engine cylinder is visualized up to 36000 frames/seconds.	Waterfall *et al.* (1996)
8	28	200	A wet gas separator can be imaged.	Yang *et al.* (2004)
12	66	100	Three phase flow of oil-gas-water can be measured.	Yang *et al.* (1995)
16	120	50	Nylon polymerization procedure is imaged.	Dyakowski *et al.* (1999)

2.5.3 Electrodes Length

According to Yang, the preference is by using short electrodes as compared to long in order for small objects to be measured and achieving wide signal bandwidth. For this project, the ECT is used to detect core sample of rock, which is small in size, therefore a short electrodes is indeed being preferred compared to the long one.

For a usual ECT sensor, the diameter is between an inch (2.5cm) and 4 inch (10cm). Yang suggested that the length of electrode shall be made larger than the diameter of the ECT sensor[12]. This is to ensure the sensor can evade a serious fringe result at both ECT sensors' axial ends. In his study, Yang *et. al.* mentioned that, as the fringe effect is greater, it will causes difficulties with the image reconstruction of 2D[13].

2.5.4 External and Internal Electrodes

The configuration of electrode is dependent on the application of the sensor. There are two kinds of configuration, external electrodes configuration and internal electrodes configuration. By opting for external electrodes, they shall be placed inside the insulating frame. For internal electrodes, they shall be placed outside the insulating frame of the ECT sensor.

2.5.5 Earthed Screen

Having and earthed screen is important to avoid interference or external noise. Interference will occur between the sensor's applied signal and any devices present close to it. Although the common practice is to place two earthed axial end screens at both ends of measurement electrodes, this practice will yield negative result on the capacitance measurement. This is due to the electric field being hauled to the earthed axial end screens.

According to Yang, earthed radial screens are used to decrease the standing capacitance between adjacent electrode pairs[14]. In addition to that, this practice will not result in negative effect on the capacitance measurement.

2.5.6 Normalization of Measurement

In ECT, normalization technique is utilized for calibration between fixed points. For calibration, the measurement is taken from a lower permittivity material, C_l to higher permittivity materials, C_h, to acquire the full range variation in the measured capacitance[13]. All the subsequent capacitance values C_m are then normalized to have values C_n between "0" (at the phase where the sensor is occupied with low permittivity material) and "1" (at the phase where the sensor is occupied with high permittivity material) according to the equation 10[13]:

$$C_n = \frac{C_m - C_l}{C_h - C_l} \qquad \text{Eq. (10)}$$

C_l = Lower permittivity material

C_h = Higher permittivity material

C_m = Represent measured capacitance value

2.6 Porosity Distribution Measurement Method

Every material on earth has its own dielectric properties. The porosity distribution measurement using ECT is based on the concept of detecting the dielectric constant of the material. For this project, distilled water saturated sandstone is being used as the subject of experiment. As sandstone contains pore space, it is filled up with distilled water. ECT will take the measurement by calculating the capacitance change when measuring different dielectric constant of the material inside the saturated sandstone.

Measurement of porosity using electrical capacitance tomography can be done by calculating the color pixel of tomogram image generated from the data acquisition system. The basis to construct the image of porosity tomography is based on the permittivity distribution of two materials having dissimilar relative permittivity inside the sensor. According to Donthi, permittivity distribution occurs when two materials are having different permittivity react inside the sensor[15]. To measure the permittivity distribution, the sensor is surrounded by capacitance electrode. As the optimum number of electrode used in the design of the sensor is 12, the number of independent electrode capacitance that can be measured is 66, and it will be projected onto a (32 X 32) square pixel grid to generate permittivity distribution image. An image can only be created on the pixels which lie on the cross sectional view of the vessel. The pixels which lied outside of the cross sectional view are unusable and neglected. On a (32 X 32) square pixels grid that contains 1024 pixels, only 812 pixels are required to construct the cross sectional image of the core sample.

There are several techniques that can be used to construct the image of permittivity distribution, like Linear Back Projection (LBP) Method, Iterative Reconstruction (IR) Method, Singular Value Decomposition (SVD) Method and others[16]. According to Gramio *et. al.*, Linear Back Projection method is usually being used as the image reconstruction algorithm as it has an advantage of producing image at quick rate, yet the accuracy is not very good[17]. Despite the lack of accuracy, LBP is sufficed the industry requirement to be used as the image reconstruction algorithm for permittivity distribution[15].

The distribution of permittivity of a mixture of two fluids is often displayed as a series of normalized pixels located on a (32 X 32) square pixel grid. Appropriate color scales are used to indicate the normalized pixel permittivity. Pixel values representing the lower permittivity material used for calibration have the value zero, shown in blue, while the pixels representing the higher permittivity material have the value 1, shown in red. The normalized permittivity distribution refers to the fractional concentration distribution of the higher permittivity material.

The Linear Back Projection (LBP) Method will be used to determine the permittivity distribution from the measured capacitance. The relationship between capacitance and permittivity distribution can be approximated and written in a linear normalized form as in equation 11:

$$B = SX \qquad \text{Eq. (11)}$$

B = Normalized capacitance matrix

S = Transducer sensitivity matrix (contains the set of sensitivity matrices for each electrode pairs)

X = Pixel gray level matrix (normalized permittivity)

Although the image of tomogram is first constructed using Linear Back Projection Method (LBP), the quality of the image can be further improved by using off-line iterative LBP image reconstruction algorithm[18]. Therefore, the quality of the image can be further improved without jeopardizing the time taken to reconstruct the image during the online measurement.

2.7 Data Acquisition System

The data acquisition system used for ECT technique would be ACECT system. It was designed and developed by ECT Instrument Ltd, which is based on an AC capacitance measuring circuit with high frequency sine-wave excitation and phase sensitive demodulation. The ACECT system can acquire image data from a 12-electrode ECT sensor at up to 140 frames per second and can reconstruct online images at up to 100 frames per second

CHAPTER 3

METHODOLOGY

3.1 Project Activities

The topic selected for the Final Year Project (FYP) is based on the field of study which is Petroleum Engineering, where the lesson learnt can be implemented for future purposes. To start with the project activities, reading journals, research papers and books related to the design of ECT sensor and Porosity measurement are part of the literature review writing. The list of journals, research papers as well as books is written in the Reference section of the report. Based on the concept written in the literature review, the research methodology is continued in the design part of the ECT sensor. For detecting porosity measurement in the core sample, the ECT comes with 8 electrodes with copper strip used as the conductive material. The electrodes are placed side by side, with the distance between the electrodes are kept equal to each other. During the fabrication stage, hardware materials are needed to construct the sensor like PVC pipe as the insulating body of the sensor, while copper strips are used as the capacitance electrode for the sensor.

The AC based ECT (ACECT) System is utilized as a tool for calibrating the sensor and measuring the porosity online. A low and high calibration is conducted so that sensor will detect porosity in the range of the lowest permittivity material and highest permittivity material. The core sample will be slotted along the location of the electrode in the sensor, so that measurement of porosity can be taken.

To capture data and analyzing it, data acquisition system is used and connected to computer to determine the capacitance and for the image reconstruction. The results are recorded, and compared to the other porosity measurement technique like Helium

Porosimeter and Water Saturation. The Helium Porosimeter and Water Saturation porosity measurement technique is conducted in the Petroleum Engineering Department Laboratory.

The data obtained from ECT sensor measurement is then compared with the standard method to obtain porosity from the laboratory, using helium porosimeter method and water saturation method. Explanation and procedure for both methods are explained in the literature review section.

To measure the effectiveness of measuring porosity using ECT sensor, for comparison of purpose, other porosity measurement technique is also being conducted for this project like by using Helium Porosimeter and also Saturation Method. The result of the porosity percentage from both measurement techniques are then compared with the porosity measured using ECT sensor.

Analysis will be done to determine the effectiveness of measuring porosity using ECT. In addition, the image tomogram of porosity distribution will be studied in chapter 4.

3.2 Procedure Identification

3.2.1 Process Flow

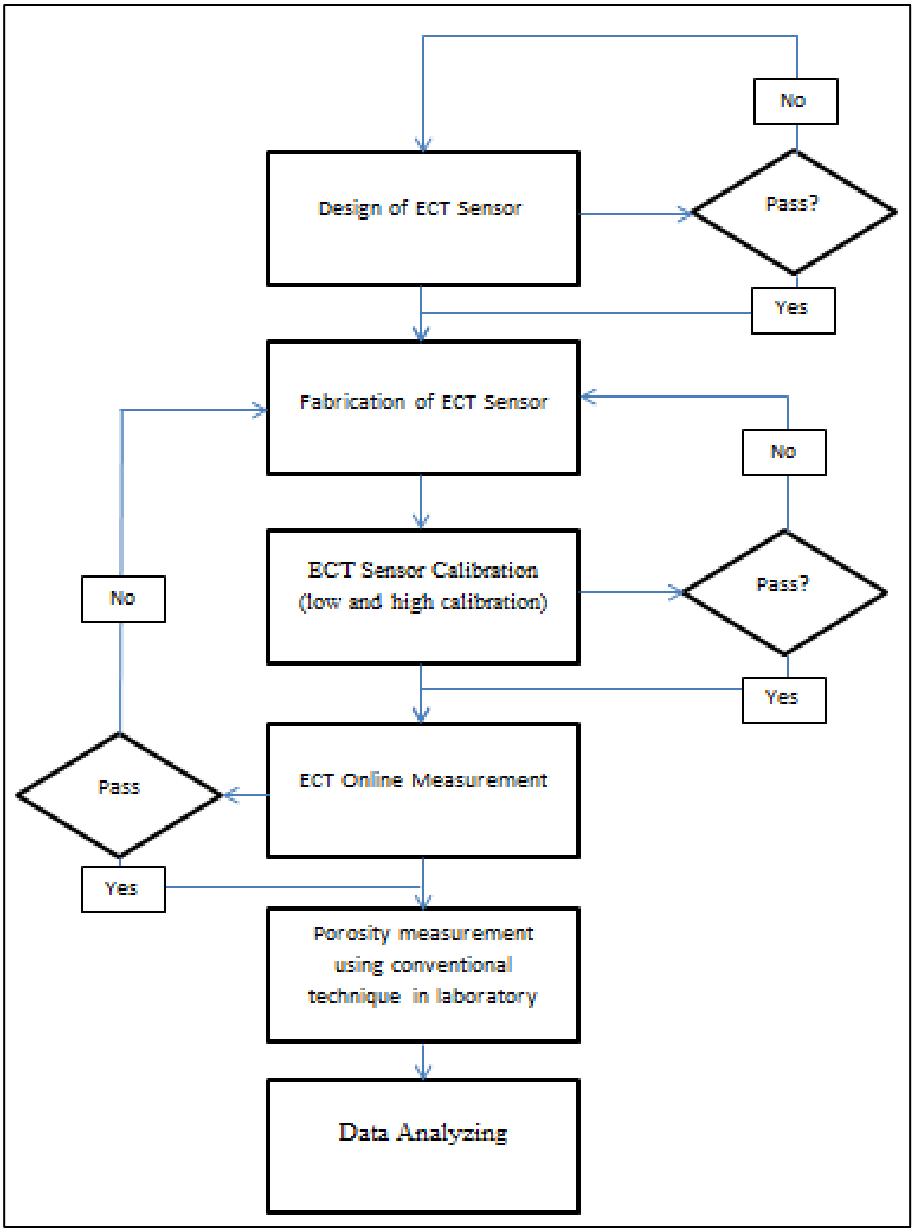


FIGURE 5. Process Flow

3.2.2 Key Milestones

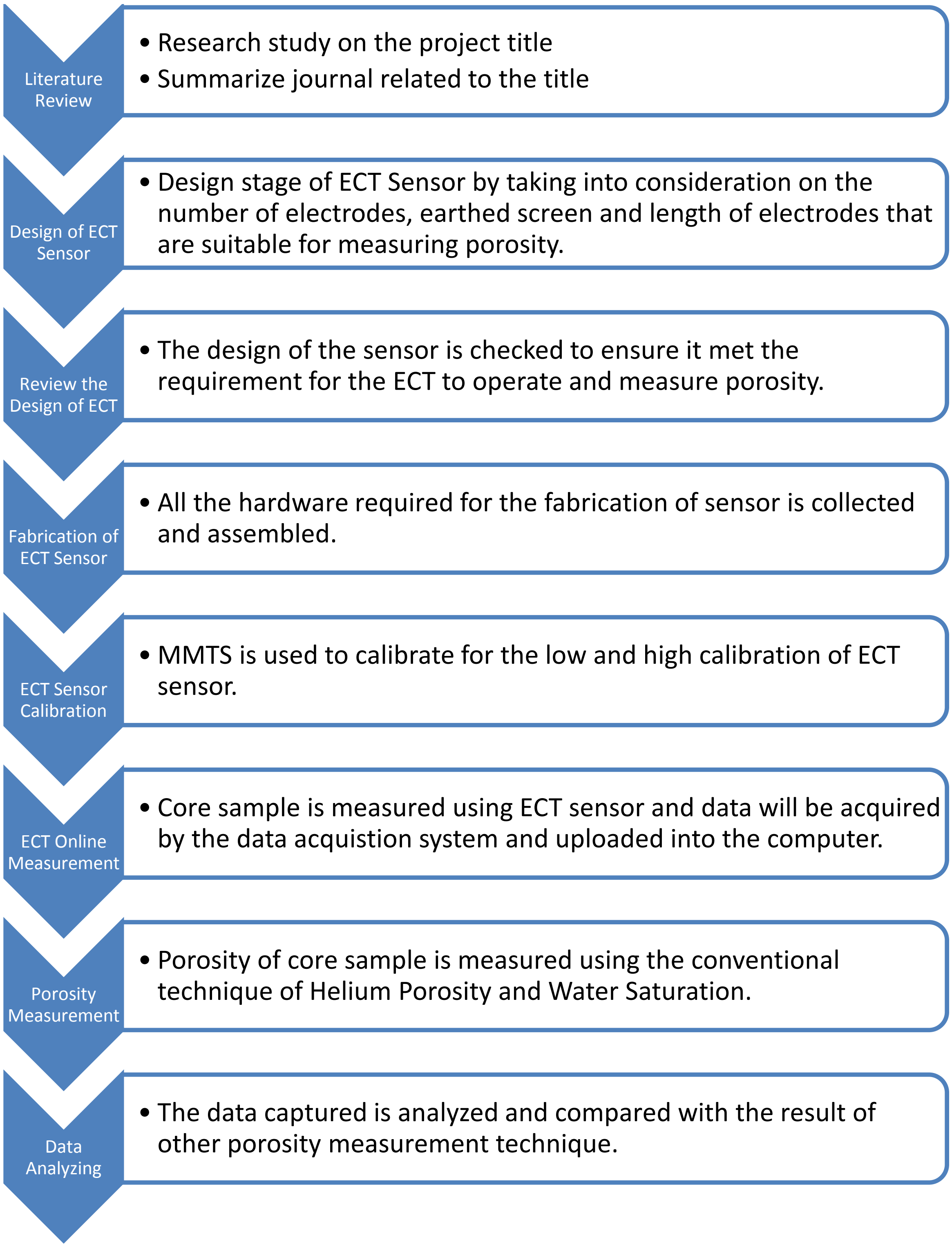


FIGURE 6. Key Milestones

3.2.3 Gantt Chart

The overall progress and key milestones of the Final Year Project 1 is displayed in the gantt chart. Project title was selected in Week 1. Literature review covered from Week 3 until Week 6. The Extended Proposal was submitted in Week 6, while in Week 9, Proposal Defense took place. Starting from Week 10, the ECT is started to be fabricated. To conclude the FYP 1 progress, Interim Report was submitted in Week 14. Figure 7 shows the timeline for FYP 1.

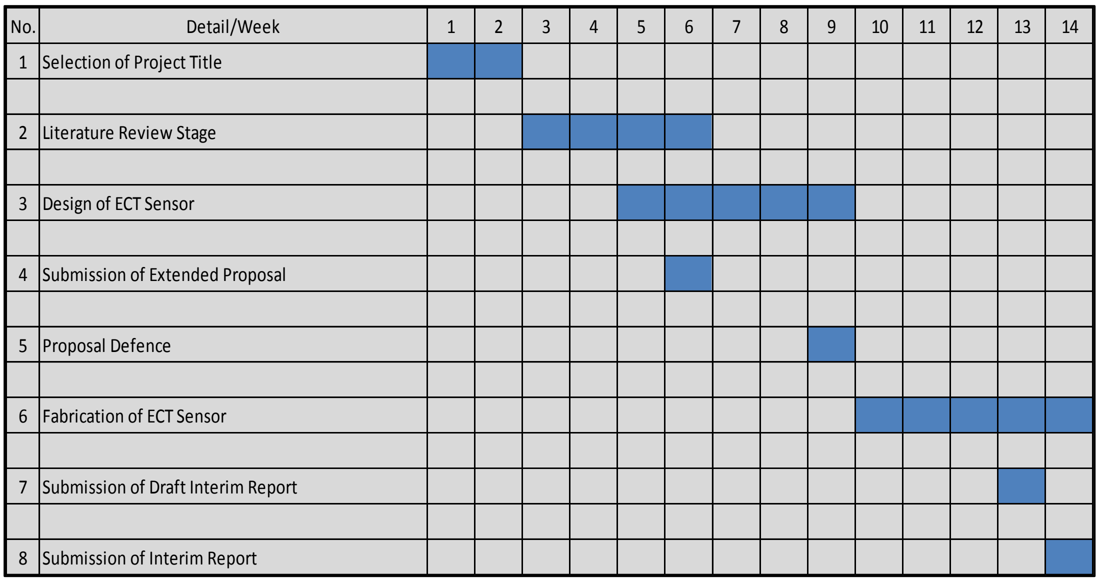


FIGURE 7. Timeline for FYP 1

Final Year Project 2 will start during the next semester. Therefore, the gantt chart shown the expected key milestones and overall progress to be completed in FYP 2. As the ECT sensor expected to be finished during the FYP 1 timeline, the FYP 2 starts with measuring activity of porosity using ECT and the conventional technique in laboratory. Data Analyzation from all measuring technique is expected to be done in Week 5. During Week 7, Progress Report will be submitted for review. The final report, with hard bound cover, shall be expected to be submitted in Week 14. Figure 8 shows the timeline for FYP 2.

No.	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
9	Porosity Measurement Activity using ECT	■	■												
10	Porosity Measurement using Other Techniques			■	■										
11	Data Analyzation from all Measurement Technique					■	■								
12	Submission of Progress Report							■							
13	Completing Final Report								■	■	■				
14	Pre - SEDEX										■				
15	Submission of Draft Final Report											■			
16	Submission of Dissertation (soft bound)												■		
17	Submission of Technical Paper												■		
18	Viva													■	
19	Submission of Project Dissertation (Hard Bound)														■

FIGURE 8. Timeline for FYP 2

3.3 Tools and Equipment

To fabricate and measure porosity using ECT sensor, certain software and hardware are required. The lists of hardware and software are tabulated in table 3 for the project:

TABLE 3. Tools and equipment

No.	Software/Hardware	Descriptions
1	Polyvinyl Chloride (PVC)	Used as the main body of the sensor.
2	Copper Tape	Acting as the capacitance electrode to measure porosity of rock sample.
3	ACECT	Used for calibration, data acquisition, data processing and data analyzing.
4	Data Cable and SMB Plug	Data cable and SMB plug are used to connect the sensor to the ITS Data Acquisition System.
5	Soldering Iron and Lead	Used to solder data cable terminal to copper tape.
6	Core sample	Used as the medium of porosity measurement.

3.4 Experimental Procedure:

Preparation of Core Sample

1. The core sample is prepared. It is immersed in a beaker filled with distilled water.
2. The core is left for several hours in the vacuum pump for the pores to be fully saturated with water.

Calibration of ECT Sensor

1. Connect the ECT system to the data acquisition system via coaxial cables.
2. The sensor is first calibrated with a low permittivity material. For this experiment, the sensor will measure air to get the value of lowest permittivity material inside the sensor, which is air.
3. The sensor is then calibrated with a high permittivity material. For this experiment, the sensor will be fully filled with distilled water to get the value of distilled water permittivity.

Online Measurement

1. The saturated core sample with distilled water would be then retrieved from the beaker full of water.
2. The saturated core sample would be then placed inside the region surrounded by electrode inside the sensor.
3. The sensor would then transmit the data through the data acquisition system.
4. A tomography image would be constructed on the processing computer.

Other Measurement Techniques

1. Porosity of core sample would then be measured using helium porosimeter. The core sample would be exactly the same as the core sample used by ECT sensor measurement technique.
2. Porosity of core sample is measured using water saturation technique. The core sample would exactly be the same as the core sample used by ECT sensor and Helium porosimeter measurement.

Data Analyzation

1. Tomography image from ECT sensor would be used to determine the porosity by using this equation 12:

$$\text{Porosity(\%)} = \frac{\text{No. of Red Color Pixel}}{\text{Total Pixels}} \qquad \text{Eq. (12)}$$

2. The porosity measured using ECT would then be compared with the measurement using Helium Porosimeter and Water Saturation.
3. Efficiency of porosity measurement using ECT would be determined from the difference between both techniques.

The table 4 shows the calculation method used for data comparison to calculate the porosity of the rock sample.

TABLE 4. All calculation method to calculate rock sample's porosity

Technique	Equations	
ECT Sensor (Extracted from chapter 3.4)	$\text{Porosity(\%)} = \frac{\text{No. of Color Red Pixels}}{\text{Total Number of Pixels}}$	Eq. (12)
Helium Porosimeter (Equations extracted from chapter 2.2.1)	$\text{Pore volume} = \frac{P_{\cdot ref}}{P_{\cdot exp}} \times V_{\cdot ref} - V_{\cdot dead}$	Eq. (4)
	$\text{Grain Volume} = (\text{V.matrix} + \text{V.ref}) - \frac{P_{\cdot ref}}{P_{\cdot exp}} \times V_{\cdot ref}$	Eq. (5)
	$\text{Bulk Volume} = \left(\frac{\pi D^2}{4}\right) \times L$	Eq. (6)
	$\text{Porosity}, \emptyset = \left(\frac{\text{Bulk Volume-Grain Volume}}{\text{Bulk Volume}}\right) \times 100$	Eq. (3)
Water Saturation (Equations extracted from chapter 2.2.2)	$\text{Pore Volume}, V_P = \left(\frac{W_W - W_d}{\rho_{water}}\right)$	Eq. (7)
	$\text{Porosity}, \emptyset = \left(\frac{\text{Pore Volume}}{\text{Bulk Volume}}\right) \times 100$	Eq. (1)

CHAPTER 4

RESULTS

4.1 Sensor Design

The sensor design was confirmed after extended research and improved understanding on the sensor. Figure shows the materials required to be considered in the design and fabrication of Electrical Capacitance Tomography (ECT) Sensor. The figure 9 shows the sensor design, by visualizing the overall body of the sensor, the measurement part, the ground electrodes and the outer casing of the sensor.

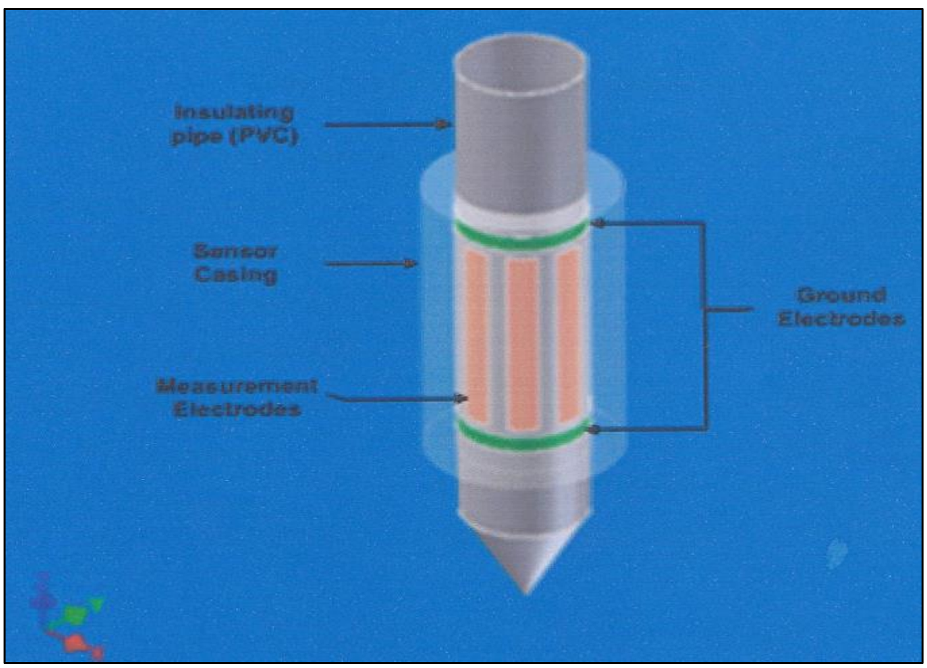


FIGURE 9. Sensor design

Table 5 and table 6 shows the specifications lists of the ECT sensor, which stated the electrodes number, electrodes length and width, the distance between two electrodes, ground electrode width and also the inner and outer diameter of PVC.

TABLE 5. ECT sensor specification for eight electrodes

No.	ECT Sensor Components	Specifications
1	Electrodes number	8
2	Length of electrodes	10.00 cm
3	Width of electrodes	0.85 cm
4	Distance between two electrodes	0.65 cm
5	Ground electrodes width	1.00 cm
6	Diameter of Inner PVC	4.30 cm

TABLE 6. ECT sensor specification for twelve electrodes

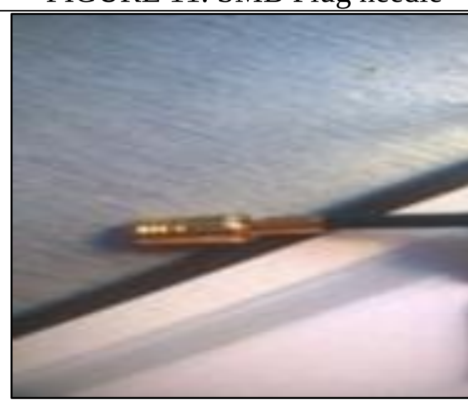
No.	ECT Sensor Components	Specifications
1	Electrodes number	12
2	Length of electrodes	10.00 cm
3	Width of electrodes	0.70 cm
4	Distance between two electrodes	0.50 cm
5	Ground electrodes width	1.00 cm
6	Diameter of Inner PVC	4.30 cm

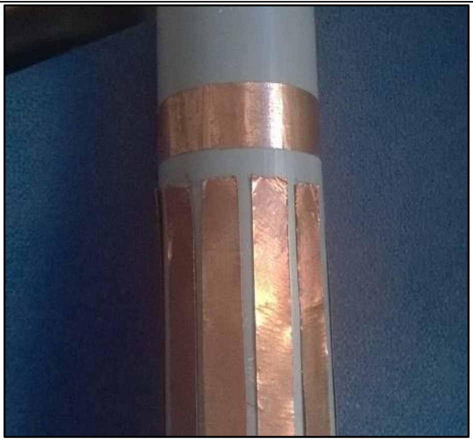
For this project, two ECT sensors are being developed to determine the possibility of using ECT to measure porosity distribution in core sample. Using different electrodes will result in different image quality during the online measurement stage. The result from both sensors will be compared in order to get the most suitable electrode number to be used to measure porosity distribution.

4.2 Sensor Fabrication

The figures in table 7 will describe the steps which have been taken to fabricate the sensor, while the materials needed to fabricate the sensor are gathered in the Table 3.

TABLE 7. Sensor fabrication steps

No.	Steps	Images
1	The wire are prepared with SMB Plug:	
	a. The SMB Plug portion is gathered.	 FIGURE 10. SMB Plug
	b. The SMB Plug needle is soldered with the gold multi core wire.	 FIGURE 11. SMB Plug needle
	c. The SMB Plug is assembled with the wire.	 FIGURE 12. Final product of SMB Plug

2	The diameter of the PVC is measured. The length of the electrode would then be decided. The copper strips, acting as the electrodes, are glued around and on the PVC. Above and below of the measurement electrodes, ground electrodes are placed.	 FIGURE 13. Measurement electrode
3	The silver multi core wires are soldered on the ground electrodes, while the gold multi core wires are soldered on the measurement electrodes.	 FIGURE 14. Soldering wire on electrode
4	ECT is then wrapped with earth shield which connected with the ground electrodes at both ends of the measurement electrodes.	 FIGURE 15. Earth shield wrapped around sensor

To assemble the wire connection to the copper as well as to the SMB Plug, soldering technique is used. The first step is to prepare the wire to the SMB Plug. The second step would be to paste the copper strip onto the PVC body. The third step is to connect the wire to the copper strip to both ground and measurement electrodes. The fourth step would be to connect a jumper wire from top ground electrode to the bottom ground electrode. The final step is to cover the portion of ground and measurement electrode with the earth shielding using zinc.

4.3 Calibration Measurement

Before the measurement of porosity could take place, calibration must be done to get the lower permittivity material and the high permittivity material. The measurement of porosity from the core sample must be from the range of low and high permittivity.

By connecting the SMB Plugs of the 8 electrodes of the ECT sensor to the data acquisition system, which is the AC-based Electrical Capacitance Tomography (ACECT) System, calibration of low and high permittivity material can be taken.

For low permittivity material, dry core sample is used as the low calibration as shown in figure 16, with figure 17 showing the result of the low calibration.

FIGURE 16. Dry sandstone

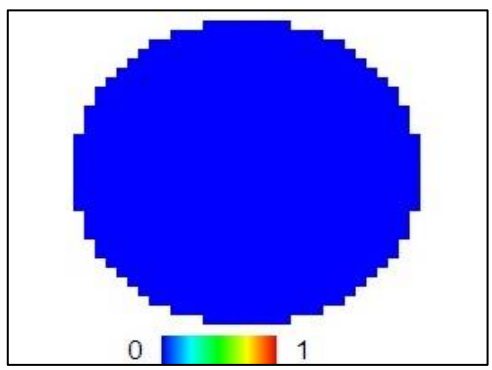


FIGURE 17. Low calibration result

For high permittivity material, figure 18 showed distilled water, used as the high calibration. Figure 19 showed the calibration result of high calibration.

FIGURE 18. Distilled water

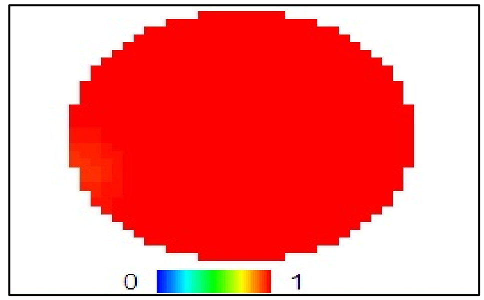


FIGURE 19. High calibration result

4.4 Core Sample Preparation

To identify the porosity of the core sample, the distilled water is used to fill up the pore spaces inside the core samples. The wet core sample is prepared by saturating it with distilled water in vacuum chamber and vacuum pump for six hours. To ensure the core samples are fully saturated with water, a measurement in terms of weight is being carried out for all three core samples. The results of the saturation of distilled water to the core sample are tabulated in table 8.

TABLE 8. Weight of core samples

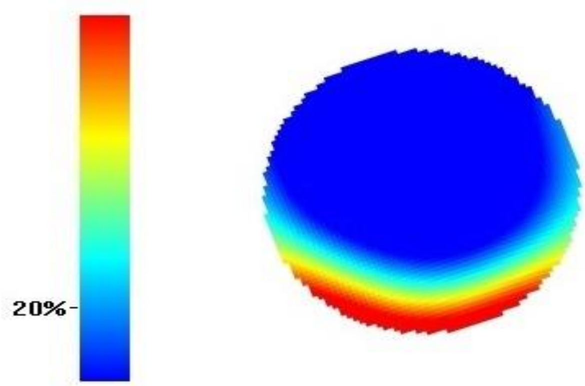
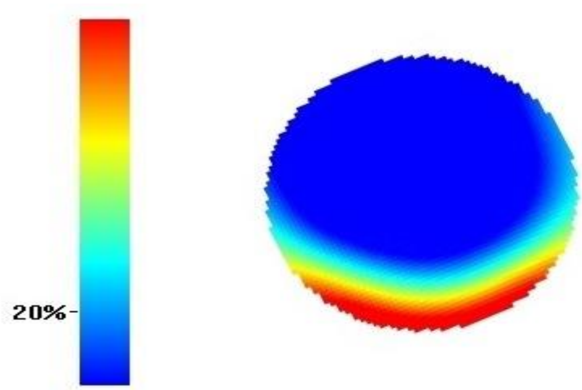
Core Samples	Before (Dry Core Sample)	After (Wet Core Sample)
Core 1	160.638	173.845
Core 2	157.826	170.980
Core 3	174.501	188.210

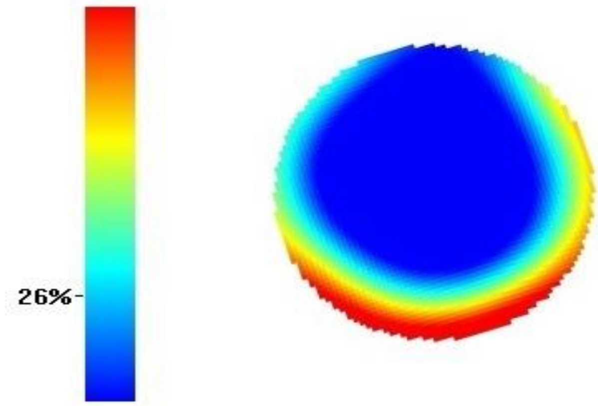
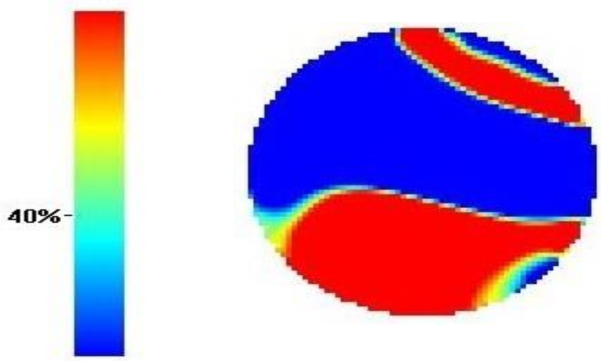
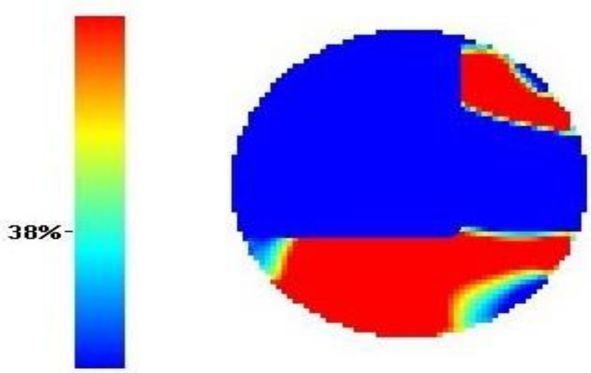
The weight of the core samples are being measured right after the saturation process. An increase in terms of weight for all three core samples indicated they have been saturated, where distilled water entered the pore space of the core samples.

4.5 Online Sensor Measurement

During the online sensor measurement, the result of porosity measurement image distribution can be found in Table 11. The result shows the measurement conducted by using both 8 electrodes ECT as well as by using 12 electrodes ECT. The type of core sample used for this project would be Berea Sandstone, as it is widely available and being used throughout the industry. All core samples are having the same diameter and length. The blue color showing the dry core sample which is not occupy by water while the red color shows the porous space in the core sample which is occupied by the distilled water.

TABLE 9. Image of porosity distribution using ECT

Core Samples	Image Distribution (eight electrodes)	Percentage (%) of porosity distribution in ECT image pixel
Core 1		20%
Core 2		20%

Core 3		26%
Core Samples	Image Distribution (twelve electrodes)	Percentage (%) of porosity distribution in ECT image pixel
Core 1		40%
Core 2		38%

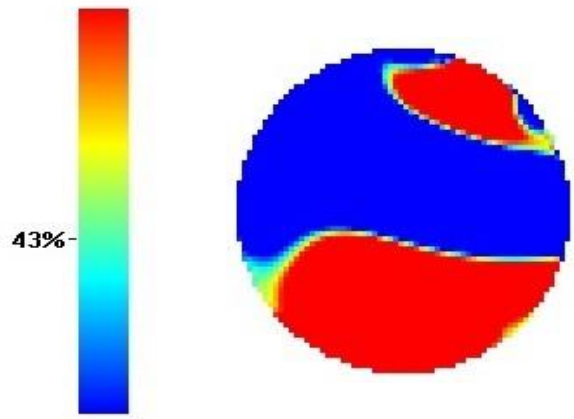
Core 3		43%

TABLE 10. Summary of porosity distribution percentage using ECT

ECT Electrodes	Core Sample	Percentage of porosity distribution (%)
8	Core 1	20
	Core 2	20
	Core 3	26
12	Core 1	40
	Core 2	38
	Core 3	43

The results of measurement and images are posted in the table 9 while table 10 shows the summary of porosity distribution percentage using ECT. As the core samples have much more porosity, it can store more water inside it. Therefore, the color scale of the tomogram image moves from blue to red. The red color indicates that they contained more water inside it, thus will indicate the porosity of the core sample, as the water is occupying the porous space inside the rock.

The ACECT system, the data acquisition system used to collect and analyze data from ECT, would do the calculation by calculating the color scale in the image of porosity distribution using equation (14), to get the value of porosity distribution.

For Core 1, the porosity distribution is at 20% by using eight electrodes ECT, while it is at 40% by using twelve electrodes ECT. For Core 2, the porosity distribution is at 20% by using eight electrodes ECT, and it is at 38% by using twelve electrodes ECT. For Core 3, the porosity distribution is at 26% by using eight electrodes ECT, and it is at 43%, by using twelve electrodes ECT. Using two sensors with different design, in this case, the number of electrodes used, yield different values of measurement. The reason of the different values of measurement is further discussed in the discussion part.

From the result of porosity distribution measurement using ECT, the tomogram images are showing almost the same pattern of porosity distribution. The red color region indicating it is populated with high permittivity material, in this case, distilled water. For eight electrodes ECT, the distribution is concentrated only at the bottom of the tomogram images for all three core samples. For twelve electrodes ECT, the distribution is concentrated again at the bottom of the tomogram images, while there is slight red region concentration at the top of the tomogram images.

Based on the distribution pattern, it is assumed that the distilled water is concentrated at the bottom of the core sample, due to gravitational effect as during the measurement stage; the sensor is being placed in horizontal. Therefore, the ECT detected the region with the most porosity distribution at the bottom of the core sample. The results of online measurement is then being compare with the standard technique in measuring porosity in the laboratory, using Helium porosimeter and water saturation.

4.6 Measurement Results

Apart from ECT Image Distribution technique, helium porosimeter and water saturation technique are used to measure the porosity of core samples.

TABLE 11. Porosity measurement using helium porosimeter

Core Samples	Porosity
Core 1	18%
Core 2	18%
Core 3	19%

TABLE 12. Porosity measurement using water saturation

Core Samples	Porosity
Core 1	18%
Core 2	18%
Core 3	19%

The result of measuring porosity using both water saturation and helium porosimeter techniques are the same for each identical core samples. The values are tabulated in table 11 and table 12. For core sample 1, the porosity is at 18%. Core sample 2 is also posting the same value of porosity, which is at 18%. The core sample 3 porosity value is at 19%. With the results, they are going to be used for comparison purposes.

4.7 Discussions

The ECT sensor consists of several parts like measurement electrodes, placed outside of the PVC pipe, while two ground electrodes are placed on above and below the measurement electrodes. A piece of zinc is used as an earthed screen to cover the region of measurement electrodes.

For this project, two ECT sensors with different electrodes number are designed and fabricated to measure porosity distribution. The first one to be designed and fabricated is ECT with 12 electrodes. This sensor could not work properly, as it is hard to be fabricated. Therefore, the result obtained during the online measurement is not satisfactory, as the porosity measurement using ECT 12 electrodes are more than double from the measurement using helium porosimeter and water saturation technique. The difference in result could be due to error from fabrication of ECT.

In order to improve the measurement result, the ECT with 8 electrodes are designed and fabricated. Due to less number of electrodes, the sensor is much easier to be developed, and based on the result in table 12; the measurement result using 8 electrodes ECT is much closer to the true value of porosity for all three core samples.

During calibration, the sensor is held horizontally. For the low calibration process, dry sandstone core sample is used, while for the high calibration process, distilled water is used. In order to determine the validity of the calibration process, the average capacitance value of high calibration process must be greater than the average capacitance value of low calibration process.

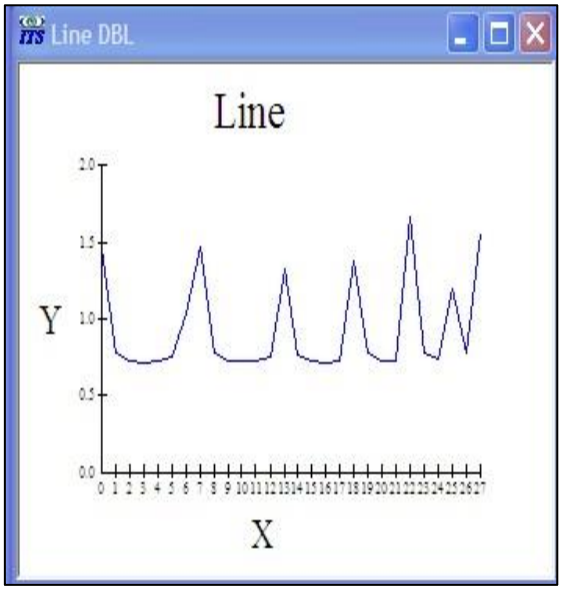


FIGURE 20. Average capacitance value for low calibration

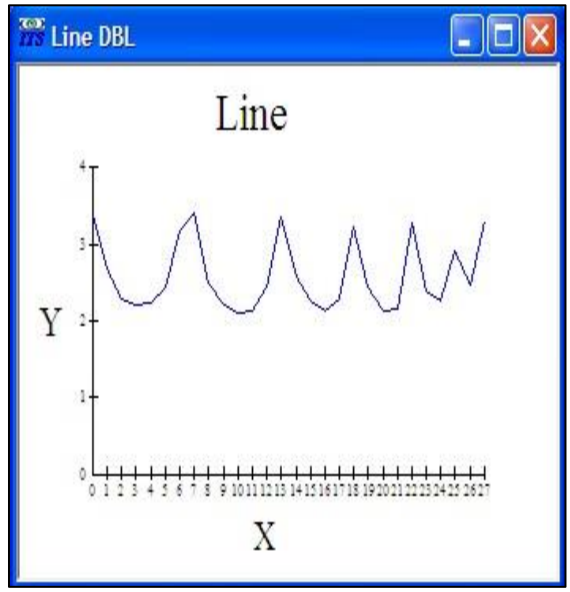


FIGURE 21. Average capacitance value for high calibration

The value of average capacitance for high calibration is between 2 to 4 based on figure 21, while for low calibration, it is in between 0.5 to 2.5 on figure 20. As long as the average value of capacitance does not reach number less than zero, the sensor is working fine.

Three sandstone core samples are being prepared for the project. The core samples are saturated with distilled water before being used during the online measurement stage. During the online measurement, the saturated core samples are placed in the section inside the measurement electrodes region. When measuring, the color scale will move from blue color of low permittivity material to red color of high permittivity material, to indicate the region that contains water in the pore space of the core sample.

To measure the effectiveness of using ECT as a tool to measure porosity distribution, Helium porosimeter and water saturation are conducted to the same core sample used during the online measurement stage.

The Helium Porosimeter technique and water saturation are the standard porosity measurement technique used in laboratory; therefore the result for both water saturation and ECT Image Distribution techniques are being compared with the result from Helium Porosimeter and water saturation. Based on the result, we could see there are huge differences of porosity percentages for all three core samples.

TABLE 13. Comparison of result (8 electrodes) with helium porosimeter

Core Samples	Porosity (%)		Percentage Difference (%)
	ECT (8 electrodes)	Helium Porosimeter	
Core 1	20	18	2
Core 2	20	18	2
Core 3	26	19	7

TABLE 14. Comparison of result (8 electrodes) with water saturation

Core Samples	Porosity (%)		Percentage Difference (%)
	ECT (8 electrodes)	Water Saturation	
Core 1	20	18	2
Core 2	20	18	2
Core 3	26	19	7

Based on the table 13 and table 14, the measurement results by using ECT is not far off from the measurement results using both helium porosimeter and water saturation techniques. To determine the effectiveness, calculation of percentage error must be done as stated in equation 13.

$$\text{Percentage Error} = \frac{\text{ECT Result-Helium Porosimeter Result}}{\text{Helium Porosimeter Result}} \times 100\% \qquad \text{Eq. (13)}$$

TABLE 15. Percentage error using 8 electrodes ECT

Core Sample	Percentage Error (%)
Core 1	11.11
Core 2	11.11
Core 3	36.84

Based on the table 15, the core sample 1 and core sample 2 show measurement using ECT yields percentage error of 11.11% from the true value of porosity when using helium porosimeter. From core sample 3, the measurement using ECT yield 36.84% error from the true value of porosity using helium porosimeter. Although for core sample 1 and 2, the error is still manageable as they are close to the true value of porosity, yet for core sample 3, the error is more than 20%. Therefore further adjustment must be made in order to improve the effectiveness of using ECT as a tool to measure porosity.

TABLE 16. Comparison of result (12 electrodes) with helium porosimeter

Core Samples	Porosity (%)		Percentage Difference (%)
	ECT (12 electrodes)	Helium Porosimeter	
Core 1	40	18	22
Core 2	38	18	20
Core 3	43	19	24

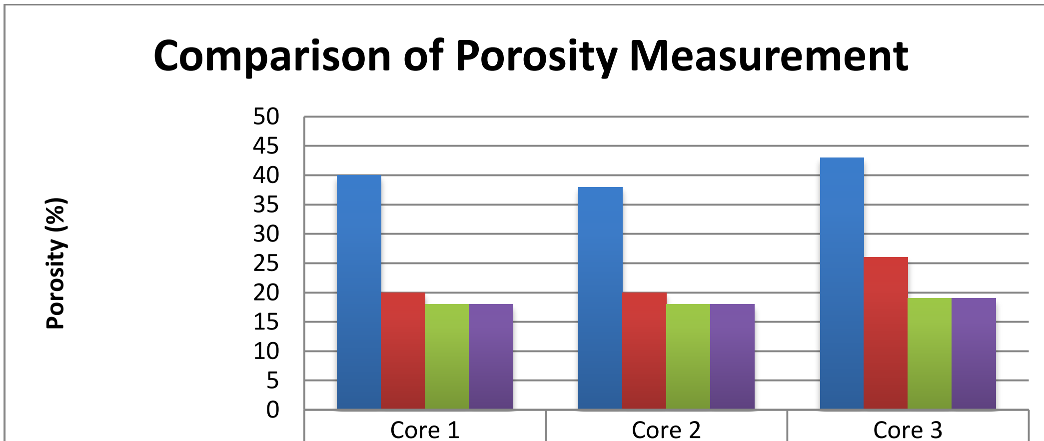
TABLE 17. Comparison of result (12 electrodes) with water saturation

Core Samples	Porosity (%)		Percentage Difference (%)
	ECT (12 electrodes)	Water Saturation	
Core 1	40	18	22
Core 2	38	18	20
Core 3	43	19	24

TABLE 18. Percentage error using 12 electrodes ECT

Core Sample	Percentage Error
Core 1	122.22%
Core 2	111.11%
Core 3	126.32%

Based on the result posted in the table 16 table 17 and table 18, the percentage error of using ECT 12 electrodes are over 100% for all three core samples, thus indicating by using ECT 12 electrodes, it would not be effective to measure porosity.



	Core 1	Core 2	Core 3
ECT (12 electrodes)	40	38	43
ECT (8 electrodes)	20	20	26
Water Saturation	18	18	19
Helium Porosimeter	18	18	19

FIGURE 22. Graph of comparison of porosity measurement of all techniques used

The results from all measurement of porosity are being compared in the graph form in figure 22. Measurements using 12 electrodes are definitely not effective as they posted more than double the amount of measurement result by using ECT 8 electrodes, water saturation and helium porosimeter technique. There are several reasons for the ineffectiveness of using ECT as tool to measure porosity. Errors could come from:

1. Fabrication stage

During the start of the project, it was intended to use ECT with 12 electrodes as the tool to measure porosity distribution in the core sample. However, ECT with 12 electrodes shows more than 100% error from the true value of porosity. Errors could come from fabrication part. The ECT with 12 electrodes is hard to fabricate, thus, errors could come from improper soldering of wires to the measurement electrodes, measurement electrodes are not attached properly on the flat surface and also the SMB plug are not connected to the data acquisition system. All these errors contribute to the large measurement of porosity distribution during the online measurement stage.

Due to huge amount of percentage errors by using 12 electrodes, 8 electrodes ECT is designed and fabricated to measure the porosity distribution. Based on the three core samples tested for determining the effectiveness of the ECT in measuring porosity, the results are much more encouraging as based on the three core samples tested, two of them posted less than 12% errors, while the third core samples posted 36.84% error.

The ECT with 8 electrodes are carefully fabricated and handled, and the result shown based during the online measurement stage is much better. Therefore the huge percentage errors could come from the fabrication of ECT sensor with 12 electrodes.

2. Calibration Stage

To do measurement using ECT, calibration must be done in order to have the measurement result in the boundary of the lowest permittivity material and highest permittivity material in the sensor. As the sensor is held horizontally throughout the whole process, the calibration of the low and high permittivity material may not be done correctly. In this case, by using core sample and distilled water, there may be some gap between the core sample and distilled water to the wall of the sensor that is not being fully occupied during calibration, thus resulting in error. As shown in the figure 23, the size of the sensor body is bigger than the size of core sample, thus leaving some gap between the core sample and the sensor’s wall which is filled with air during calibration. The presence of air in the calibration will definitely affected the measurement result.

FIGURE 23. Gap between core sample to the wall of sensor

3. Core Sample Preparation

The core sample is prepared by saturating it with distilled water in the vacuum chamber. It will take about 6 hours approximately for the core sample to be fully saturated with water. Yet, as water molecule is large, therefore it may not be able to penetrate the pore space which is not connected to each other. Therefore the overall porosity value of the core sample may not be 100% correct.

The other issue with saturation is that, the core sample is wet even at the outside of the core sample. Therefore, the ECT may detect the water which lies outside of the core and measure it as a high permittivity material in the tomogram image, thus results in errors in measurement.

4. Image of Porosity distribution

Looking at the porosity distribution of all core samples imaged by the ECT, the porosity distribution is focused at the bottom of the core samples. These could be due to the effect of gravity as water moved to the bottom of the core sample when being horizontally in the sensor. It could due to error as the sensor is most sensitive at the wall instead of the middle. As the core sample is saturated with water, it is wet even at the outside of the core sample. Therefore the sensor would most likely detect the wet surface of the core samples and defined it as the porous region which has been occupied with water.

To overcome this problem, a change in methodology of the experiment is expected to be done in the future. Currently, the core sample is saturated with distilled water before being measured with ECT. A suggestion is to inject water at high pressure so that the ECT can monitor the real time data in which region water occupying the porous space of the core sample. Perhaps the measuring electrode can be mounted outside of the Benchtop Permeability System, which is available in the lab to measure porosity. In addition to porosity, permeability can also be measured.

In future works, further optimization will be done to ensure the result of porosity measurement using ECT image distribution is not far off or accurate when compared with the porosity measured techniques used in the laboratory. In the recommendation parts there are several suggestions that can be implemented to achieve better result in future.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Based on the overall progress of the project Porosity Measurement using Electrical Capacitance Tomography (ECT) Sensor, it is consisted of several milestones from designing the sensor, fabrication of the sensor, calibration of the sensor, to measurement of porosity using ECT until the analysis of suitability of using ECT as a tool to provide image distribution and measurement of porosity.

The design of ECT is consisted of determining the material of the sensor and the amount of electrodes to be used on the sensor. Two sensors are being developed, one is using eight electrodes, and the other one is using twelve electrodes. Apart from the measurement electrodes, the other parts on the sensor consisted of ground electrodes and outer shielding to avoid interference between sensor's applied signal and any devices located nearby the sensor. Measurement electrodes are placed outside of the sensor body, again to avoid a direct contact to the measuring medium inside the body, so that the sensor's non-invasive and non-intrusive characteristics can be preserved.

Before measurement of porosity can be taken, calibration is done to indicate the low and high permittivity material that can be measured by the sensor. For low calibration, dry rock sample is used as it is the lowest permittivity material inside the sensor. For high calibration, distilled water is used as it is the highest permittivity material. When measuring, the wet rock which has been saturated with distilled water is measured, therefore, with the calibration; the ECT can help to distinguish the region of low and high permittivity material on the tomogram.

During the online measurement stage, the wet rock core sample, saturated with distilled water is being measured by the ECT sensor. Based on the result using both sensor of eight and twelve electrode, both of them are not able to provide the accurate percentage of porosity distribution in the wet rock core sample. These are due to the design and fabrication of the sensor, where less number of electrodes are used in this project, that lead to less quality image of porosity distribution, while the sensor is not up to industry standard, thus possibility of having error during measurement is high. During calibration stage, when the sensor is placed horizontally, there is gap in between the core sample and distilled water to the wall of sensor which is occupied by air, the difference of properties of air with distilled water and core sample will result in error in calibration. Once calibration stage is experiencing error, the measurement could go wrong too. In terms of preparation of the core sample, in can be further improve. The core sample may not be fully saturated with water.

This project achieved both of its detail objectives. The first one is to design and fabricate a workable sensor suitable to be used for measuring porosity. ECT with 12 electrodes is developed first, but it suffered from performance issued, thus giving huge difference in porosity measurement. ECT with 8 electrodes is developed later, and the result of porosity measurement is much more satisfactory and did not suffer from performance issue, thus proving the design and fabrication of the sensor is working.

The second objective is to measure porosity using ECT and compare the result of ECT measurement with standard technique used in laboratory, which are helium porosimeter and water saturation. ECT managed to get the measurement of porosity and the results are being compared with the standard technique. Based on the percentage error, by using ECT with 12 electrodes, the errors are more than 100%, thus make it ineffective to be used. For ECT with 8 electrodes, the errors are less than 12% for core sample 1 and 2, while less than 40% for core sample 3. The errors are more than 10%, thus it may not be accurate to use ECT as a tool to measure porosity distribution in core sample.

In conclusion, this project achieved its main objectives, which is to test the suitability of using ECT as a tool to provide image distribution of porosity. Based on the results of images distribution of porosity as well as the measurement value, the ECT is deemed not suitable to be used for measuring porosity in core sample. If all the errors have been fixed and further improvement has been made in the future, but the result is not satisfying again, perhaps the ECT may not really be suitable to be used as a tool to measure porosity.

5.2 Recommendations

Several recommendations can be applied to future project involving ECT sensor to measure porosity, especially in terms of the design. For this project, only eight and twelve electrodes are used to provide image. By opting for sixteen electrodes, a better image can be expected, where the ECT may have chance to locate the porosity distribution of the core sample.

Second, to improve the result of porosity measurement and also the tomogram image for porosity distribution, the methodology may have to be changed. The current methodology, saturating core sample with distilled water may not be suitable to get the accurate result. One suggestion is to inject water at high pressure using the device in figure 24, so that the real time data of water occupying the porous space of the rock can be observed. In fact, along with porosity, permeability can also be detected using ECT. Measurement electrodes are attached at the outer body of the high pressure water injection device.

FIGURE 24. High pressure water injection device

Third, by utilizing an industry made ECT sensor may help in the online measurement process. The ECT sensor develop by the student may suffer from performance issue as the ECT are not carefully fabricated, thus resulting in error in measurement. Soldering of the wire and assembling the SMB Plug are the two most challenging aspect of fabricating ECT, therefore the problem may come from both aspects. In addition, the ECT size must be exactly the same size as the core sample, to prevent air from occupying the gap between the core sample and the wall of ECT sensor.

Fourth, to improve the result of measurement using ECT, the core sample size must be according to the standard size used in the industry. Currently, the core sample dimension, 3 inch in length, 1.5 inch in diameter, is too small, thus the ECT may not be able to detect the correct representation of the porosity distribution of the core sample. Standard size of core sample used in the industry can be obtained from geology or mineralogy lab.

5.3 Future Works

This project will be continued using sixteen electrodes mounted around the external body of the sensor, to provide better image of porosity distribution of core sample. The sensor will also be fabricated by the industry standard to prevent performance issues. In addition, the methodology of the project can also be improved, where the result of image of porosity distribution of core sample can be compared with the result of X-Ray CT scanning. If the ECT is proven to be able to measure porosity distribution in core sample, the ECT can be implemented as a tool that can be used in down hole, to provide real time image of reservoir.

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APPENDICES

ACECT System Specification

ECT Instruments

1. Working environment

General	Laboratory conditions
Temperature	0 ~ 50°C ambient
Humidity	Without condensation
Power	110-240 V~

2. System hardware

Hardware units

Capacitance measurement board	8	2 measurement channels each board and 16 measurement channels in total
DDS signal generator board	1	Providing 2 programmable sinusoidal signals
Multiplexer	1	Compatible with Eurocase*
Backplane board	1	96 channels
PCI data acquisition board	1	With ADC, DAC and DI/DO
Ribbon cable	1	50 wires
Eurocase	1	19”

* Eurocase is a European standard for industrial and laboratory instrumentation

Hardware details

Each capacitance measurement board	Number of measurement channel	2
	Capacitance measuring circuit	Sinusoidal excitation and phase-sensitive demodulation
	Excitation frequency	Programmable up to 500 kHz (Default frequency: 200 kHz)
	Adaptive capacitance measurement range	0 ~ 2 pF (Different measurement range with different electrode pair/combination)
	Capacitance resolution	< 0.1 fF
	Signal-to-noise ratio (SNR)	> 60 dB
	Power supply	+5 V, $\pm$15 V
	Board format:	Eurocard**
	Connector to electrode	SMB
	Connector to backplane board	DIN41612 a/c-64 way plug
DDS signal generator board	Number of generators	2
	Signal type	Sinusoidal
	Signal frequency	Programmable up to 500 kHz (Default frequency: 200 kHz)
	Signal amplitude	Programmable up to 20 V_{p-p} (Default amplitude: 16 V_{p-p})
	Phase between 2 sinusoidal signals	0 ~ 360° programmable
	Power supply	+5 V, $\pm$15 V
	Board format	Eurocard
	Connector to backplane board	DIN41612 a/c-64 way plug
Multiplexer board	Number of input channels	16
	PGA gain	1, 2, 4, 8, 16
	Power supply	+5 V, $\pm$15 V
	Board format	Eurocard
	Connector to backplane board	DIN41612 a/c-64 way plug
Backplane board	Board format	Compatible with Eurocase
	Connector	DIN41612 a/c-64 way socket
Data acquisition board	Number of channels of analogue input	16
	Resolution of ADC	12 bits
	Number of analogue output	2
	Resolution of DAC	12 bits
	Number of DI/DO	24
	Computer interface	PCI
	Data acquisition rate (without online display)	>100 frames per second for a 12-electrode sensor
Power supply	Input voltage range	85-264 V~
	Input frequency	47 ~ 440 Hz
	Outputs	+5 V (3 A), +15 V (1.5 A) DC, -15 V DC (0.5 A)
	Max. power	25 W
	CE marked	Yes

Ribbon cable	Number of wires	50
	Type of connector to PC	50 pin D shape
	Type of connector to Eurocase	50 pin ribbon
Eurocase	Type	3U 84HP (19”) desk enclosure
	Approximate size	50×12×27 cm
	Weight with boards	5.1 kg

** Eurocard is a European standard and compatible with Eurocase

3. System software

Software package

System test program
Image data acquisition program
Image reconstruction programs
Data conversion program

Software details

Overall	Working environment	Windows XP
	Computer language for system software	Visual C++
System test program	Test offset	
	Test DC gain	
	Test data acquisition of a single set of capacitance data	
Data acquisition program	System calibration	
	Combined excitation electrode	1, 2 and 4***
	Acquisition of defined sets of image data	
	Calculation of normalised capacitance	
	Save binary raw measurement data	
Linear back-projection (LBP) algorithm	Generic sensitivity maps provided for 8- and 12-electrode sensors	
	Linear back-projection algorithm	
	Image display	
	Volume concentration estimation from normalised capacitance and image	
Landweber iteration algorithm	Relaxation factor	Programmable (Default value: 1.2)
	Number of iterations	Programmable
	Plus all other functions in LBP algorithm	
Binary to text conversion software	Read binary raw measurement data	
	Save text measurement data	

*** Sensitivity maps for 4-electrode combination are not provided

4. Optional (not included)

Demonstration sensor	Number of electrode	12
	Cable	RG174 A/U
	Connector	SMB
	Diameter	1.5”
	Length	21”
	Weight	1 kg
USB data acquisition board	Working with laptop	Instead of PCI board
	Number of channels of analogue input	16
	Resolution of ADC	12 bits
	Number of analogue output	2
	Resolution of DAC	12 bits
	Number of DI/DO	8
	Computer interface	PCMCIA
	Data acquisition rate	500 k sample/s****
Accessories	Cable	RG174 A/U
	Connector	SMB
	SMB plug cramp tool	
	Self-adhesive copper foil to construct sensor electrodes	

**** The overall data acquisition rate with PCMCIA interface is lower than PCI interface.

Declaration: The above specification is accurate when this document is written. Some specification may change at the discretion of ECT Instruments Ltd.

If you are interested in this product, please contact us by
Tel. +44 161 962 7923, Email: info@ect-instruments.com or sales@ect-instruments.com